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State of the Art Photocell
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1516 Ninth Street, 1st Floor
Sacramento, CA 95814

Submitted By:
Architectural Energy Corporation
2540 Frontier Avenue, Suite 201
Boulder, Colorado 80301

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Contact Information:

Subcontract Project Manager
Doug Paton
The Watt Stopper
2800 De La Cruz Blvd.
Santa Clara, CA 95050
(925)-454-8224 voice
(925)-243-8912 fax
Doug_Paton@WattStopper.com

AEC Program Director
Judie Porter
Architectural Energy Corporation
2540 Frontier Avenue
Boulder, CO 80301
303-444-4149 – Voice
303-444-4304 - Fax
jporter@archenergy.com

Prepared by:

Doug Paton, Product Line Manager, The Watt Stopper
Dr. Richard G. Mistrick, Associate Professor of Architectural Engineering, Pennsylvania State University
Francis Rubinstein, Staff Scientist, Building Technologies Department, Lawrence Berkeley National Laboratory
Dorene Maniccia, Manager, Market Segment Development, The Watt Stopper

State of the Art Photocell Final Report

Executive Summary

This report discusses the current state of the art in the design of photocontrol systems to provide continuous daylight responsive dimming, particularly in classroom applications. This report identifies currently available products and categorizes the products into typical configurations. It then discusses the product specific performance related issues identified in the published research. The last section reports on possible future development directions. At the back of the report is a list of products and manufacturers that have been identified as currently available. Individuals involved in the preparation of this report are listed on page 2. This report is Task 1 of PIER LRP Project 3.3 Classroom Photocell and Control System and provides a foundation for the rest of the work to be completed under this Project.

Introduction

This report collates information from five sources. The first is a survey of available products being sold in the U.S. and in Europe today. Our survey of products is based on a search of marketing materials available on the Internet and the limited personal experience of team members with some of the products. In preparing this report, we have not conducted any new testing to validate performance for these products. Second, we reviewed published research studies because these studies provide the only actual performance evaluations. In this report, we have referenced the findings that we believe are relevant to product design. The third source of information is the product development work conducted by Andrew Bierman at the Lighting Research Center along with Sensor Switch. Their work has resulted in a prototype product that incorporates many of the findings of Mr. Bierman's previous research in this field. Mr. Bierman has shared a sample of their design and a report, which includes his team's test results. (This work is subsequently referred to as the LRC prototype and LRC prototype report.) The fourth source of information is the team's knowledge of emerging technologies that may impact the future of these systems. Finally, as this report is written at the beginning of a two-year project, we have identified areas that the project team believes may be within the scope of the project to explore and incorporate into a prototype design.

In surveying the available products, we found more than 15 companies actively marketing the capability of providing daylight responsive dimming in the United States. However, we found little information regarding the performance and the applicability of the products. We found only limited detailed technical performance data for any of these products. The primary information provided was the photocell's cone of view. An example of such technical data is found in a study of photosensors by Bierman et al [1] that identified the three major technical components of these devices as 1) the spatial sensitivity of the photocell, 2) the spectral sensitivity of the photocell and 3) the type of control algorithm used to calculate a signal to the controlled lamps. This lack of technical information is in contrast to what is typical of other control products such as occupancy sensors where coverage patterns are routinely provided so that competing products can be compared. We also found few case studies available from the manufacturers.

Several research studies (Rubinstein et al., 1989, Rubinstein, 1984) showed that the variability of daylight throughout the day and year resulted in situations where the existing generation of controls were not maintaining adequate lighting levels or were otherwise behaving unexpectedly. [4] We found research studies, as well as anecdotal evidence, that suggest that systems had been disconnected or disabled because of poor product performance or inappropriate application of the product. From this information, it is easy to formulate the opinion that no one existing product provides the perfect solution. The perfect solution would be to provide the following on a consistent basis at a cost-effective price under a variety of different applications:

1. Provide adequate work plane illuminance and avoid over dimming.
2. Avoid drawing the occupant's attention to the dimming action by dimming too fast or making noticeable changes in the light level.
3. Provide only as little electric light as required.
4. Require minimal effort in commissioning the system.

This report will focus on control products that provide continuous dimming signals primarily to fluorescent lamps, although they could potentially work with other light sources. These control products are designed with the intent of signaling one of the four types of dimming fluorescent ballasts. The first type are ballasts referred to as "0-10 VDC" ballasts. At least 5 manufacturers market dimmable ballasts in the United States that conform to this standard. These ballasts respond to a 0-10 VDC signal to raise or lower the light output. The signal is provided over an extra two wires connected to the ballast. The standardization of control wire colors, typically violet and gray, is an example of conformance to this standard. A second type of ballast also utilizes additional control wires but in a proprietary method. Examples of this are Lutron's HiLume that requires one control wire. Another example is EasyLite's ballasts which requires two additional control wires. In both of these examples, the ballast manufacturer is also the primary, or only, supplier of compatible controls. A third type is a ballast that responds to a "phase cut" signal (e.g. Advance Mark X or Lutron Tu-Wire). Also called two-wire ballasts, these ballasts can be dimmed from an incandescent lamp dimmer and are particularly appropriate for certain applications where control wires cannot be economically added. Digitally-addressable ballasts, such as DALI (Digitally Addressable Lighting Interface), represent the fourth and final type. This type of ballast can be commanded over a communication network that is extended to each ballast. Digitally-addressable ballast have only recently been marketed in the U.S. market although they have been available in Europe for several years.

The Daylight Responsive Dimming System

We found daylight dimming systems to be constructed of four essential elements:

a. A photocell to sense the light level.
b. A control circuit or engine that changes an output based on the photocell input.
c. A control output that drives the ballasts.
d. Calibration adjustments, usually implemented as dials, which are used to establish the actual relationship between the input and the output signals.

Three different configurations

Daylight dimming systems come in three different configurations:

a. Self-contained units, often referred to as photosensors. These units contain all four elements in one unit, usually ceiling-mounted. Generally, these units are dedicated to providing daylight dimming and do not attempt to provide other lighting control functions that the more complex units often include. All of the units in this category appear to use analog electronics with no microprocessor-based products available. Typically, these units are powered by the 10 VDC signal supplied by the ballast. Within this type of unit, there is a standardization of features, generally providing control for only one zone. For example, only one of these units, PLC-Multipoint EDS offers an occupant override feature as a standard or as an option. These products are commissioned by adjusting one or more dials, jumpers or dipswitches. The one device that is an exception is the Philips TRIOS Luxsense. This device uses an adjustable aperture to limit the amount of light that the photocell sees.

A Specifier Report on Photocells was published by the National Lighting Product Information Program in 1998[2]. This report tested five models of these self-contained units (two additional units were photocells that connected to remote controls). Of the units in the study, three of the products appear to be still available today. One company is no longer in business, Etta International, and one company, The Watt Stopper, replaced the tested unit with a newer model. It is estimated that at least eight major manufacturers are currently selling a product of this type.

b. Photocell with a remote controller or setup device. Within this category, there is little standardization except that the photocell is a separate device that communicates with a controller, wall switch or setup device. The key advantage of this configuration is that the adjustments are removed from the photocell, typically placed in the additional controller or wallswitch so that commissioning can be conducted without blocking the view of the photocell. These devices may have been designed with daylighting as a core function or daylight dimming may only be one of a menu of lighting control options. All of these devices with the exception of the Lightolier Photoset are microprocessor-based products (The Lightolier product has been reported to be no longer marketed). The amount of daylight application guidance provided by the manufacturer also varies within this category. We have subdivided this category into five typical configurations based on the type and location of the additional controller or wallswitch:

1. Photocell and wall switch. Two devices fit into this configuration, the LRC prototype and Lightolier's Photoset. The wall switch provides a convenient

location for adjusting setup parameters as well as providing an occupant override. In the case of the LRC prototype, the wall switch also is used to provide ON/OFF switching.

2. Photocell and room controller. In this configuration, the second device is a metal enclosure that contains high voltage relays for switching fixtures on and off as well as providing the low voltage dimming signal. These room controllers provide an input point for occupancy sensors and wall switches as well. While daylighting is typically described as an important feature, these devices are also sold for applications in which they are not providing daylight responsive dimming. These devices generally provide one zone of dimming. These devices are intended to be distributed throughout a building, typically mounted above the ceiling of the zone controlled. The Leviton Centura, Lithonia DEQ LC and the Lutron Digital Microwatt fit into this category. Both of these products happen also to provide the ability to be networked. Also in this category is the Honeywell EL 7305. The previous version of the Lutron product, which used the current model of their photocell, as well as the Honeywell product were tested in the Specifier Reports on Photosensors.

3. Photocell and DIN-rail mounted controller. The controller must be mounted within a metal enclosure. These devices may provide a single zone of control or multiple zones of control from one photocell. The Watt Stopper LCD series, which provides one or three zones of dimming control, is included in this type, as well as the Luxmate DSI-TLC, which provides both two and nine zone models.

4. Photocell and handheld remote. In this configuration, the setup device is a handheld remote. In this instance, the ceiling mounted photosensor includes the photocell, control engine and the control output. The setup adjustments have been removed. Typical of this configuration is the Helvar Digidim.

5. Photocell integrated into a lighting fixture. The final configuration is a photocell that is an integral part of a pendant lighting fixture. The distinction here is that while most photosensors could be mounted onto a fixture, the devices in this category could never be removed from the fixture and be mounted onto the ceiling. The two known implementations in this category take very different approaches. Just Right Light integrates the control algorithm into the dimming ballast. It brings one or in some instances two fiber optic cables back to an input in the dimming ballast. The only adjustment is to increase or decrease the amount of light that is transmitted by the fiber optic cable. This system is marketed as a low tech, maintenance friendly system. While initially promoted as a daylight responsive dimming system, the marketing emphasis has changed to providing lumen maintenance. The second implementation is ErgoLight where the photocell and other controls are integrated into the pendant light fixtures. The controls are then integrated into a network to provide individual office control. All of the adjustments are made from a computer communicating over the network. The

> Ergolight system is marketed as providing the maximum in personal control; it may not be appropriate for schools.

c. Dimming Control from a Central Panel
In this configuration, a central panel location is used to provide dimming signals to four, eight or more zones. The photocell is connected to either a photocell specific analog input or a general purpose input. Typically, one photocell can be used to control as many zones as required. The photocell may be connected to the dedicated panel or be connected to a remote panel with the information shared over the network. Typically, these systems are networked and can be remotely viewed and adjusted. Daylight dimming is marketed by lighting relay panel manufacturers such as Douglas Lighting Controls, Lighting Control and Design and Cutler-Hammer. The Cutler-Hammer POW-R-COMMAND 100 requires a separate interface device to signal standard dimming ballasts. This additional requirement suggests that the dimming controller was originally designed for another use and adopted to provide dimming control.

Daylight responsive dimming is also marketed as a capability, or possible add-on, to building automation networks by their manufacturers. It is also marketed by companies, such as Triatek, which sell lighting controllers intended to reside on the building automation vendor's proprietary network. Little detailed information regarding the daylighting application is available from the manufacturers of these systems. The actual performance of these systems is unknown because little or no research has been done on them. In the last section of this report, we detail the possible advantages of a networked system including remote comparison of similar spaces, automatic collection of historical data and possible tools for commissioning. However, it is not clear from the marketing literature of these products that they provide any of these features.

The Photocell

We found all of the available photocells to be intended for ceiling mounting (or alternatively mounted in the lower face of a pendant fixture.). The ceiling is not an ideal location for a photocell because the goal of the photocell is to take a measurement of the work plane illuminance. The photocell readings are valid based on the assumption of a predictable relationship between the work plane illuminance and the photosensor signal.

Several studies have shown this ratio to be dynamic in daylit spaces. Typically, this ratio is directly or indirectly measured during commissioning but research has shown that this ratio is likely to change according to the time of day, the time of year and the sky condition. Lee et al have extensively researched variations in the sensor-signal-to-task illuminance ratio in daylit spaces.[5] Bierman found that in sidelighting applications the ceiling illuminance typically increases at a greater rate than task illuminance as daylight enters a space.[1] Mistrick et al[3] found:

> The sensor-signal-to-task illuminance ratio is generally on the order of four to five times higher for daylight than it is for electric lighting in this space.

Mistrick's study did not model the effects of toplighting, snow and other highly reflective exterior objects but suggested that they are likely to exacerbate the sensor signal to task illuminance ratios.

The ceiling location also assumes consistent reflectivity of the viewed surfaces. If the reflectivity of the surface changes, then the sensor signal could change even while the ambient light remained constant. Mistrick tested the effect of changing the reflectance of the work plane and found that a change in reflectance from 20 to 60 percent did not significantly alter the performance of the tested photosensors.[3] However, Bierman suggests that the difference in reflectivity of a black veneer desktop and white papers could vary by a factor of 10. This study also suggests greater sensitivity to highly reflective objects such as mirrors. [1] Additional concerns include the impact of semi-permanent changes such as moving furniture or a change in the use of the space.

Given the problems with the ceiling location, one might think that it is reasonable to locate the photocell more closely to the work plane. However, no real world solutions appear to have been found. A photocell product that had been designed for mounting on the desktop no longer appears to be available. Rubinstein et al described the difficulties that would be encountered if the photocell were mounted at the work plane.[4]

All of the ceiling mounted photocells, with the exception of the Lightolier Photoset photocell, were designed to view the horizontal work plane or floor below the photocell. The Lightolier Photoset product was designed to view the back wall. Mistrick found in their study of a small office that having the photocell view the back wall produced a high correlation of signal to workplane illuminance at each daylight condition.[3] This study also noted that the daylight responsive dimming system must be designed to work with the potentially expanded signal range of a photocell viewing the back wall.

However, it should be noted that viewing the back wall may not be a viable option in a majority of spaces, such as open offices or classrooms. In classrooms, especially in the lower grades, it would be typical for the use of a wall to be dynamic for displays, storage or hanging coats. Also in applications with clerestories and toplighting, the wall may be used to reflect and diffuse daylight into the room. This configuration provides a different relationship of the daylight illumination on the back wall to the ambient room levels than anticipated with a sidelighting application.

Most of the photocells had a symmetrical cone of view with its axis intended to be perpendicular to the work plane. The exceptions to having a perpendicular cone of view were the photocells intended for use in open loop systems. The Lutron digital microwatt photocell, with the microPS photosensor, is described as having a 60-degree from horizontal viewing angle. The Watt Stopper LS-190C defines the center axis of the cone at a 45-degree angle from horizontal. Lighting Controls and Design PCI photocell also appears to be angled from the product photograph but we were unable to verify the actual angle. The reason for these configurations is that these photocells are designed to view only the daylight contribution and not the electric light contribution. One other interesting configuration of a photocell is the Douglas WPC-5700 that swivels in its socket allowing the photocell to have a cone of view that is perpendicular to the work plane or a cone of view that is angled away from the window. The intent of this configuration is to allow the photocell to not view the window. We are not aware of any test data on this device.

Several studies have attempted to identify the best view of the room to sense the ambient light. In 1989, Rubenstein published a study that found that the best correlation of photocell signal to workplane illumination was from a partially shaded photocell. This photocell was equipped with an opaque baffle that blocked the view of the window but was open to view the floor and the three walls of a small office. This study further stated that the best system performance was from a partially shaded photocell matched with a closed loop proportional control.[4] It is interesting to note that today there is apparently no product that exists that matches this description. Additional studies conducted since 1989 appear to support these earlier findings. The findings of Mistrick supported the view that the photocell should not have a direct view of the window. This study found a poor correlation of the sensor input and the workplane illuminance when the sensor received input from the window.[3]

The LRC report on their prototype describes the photocell as having a symmetric and rather wide response. The report acknowledges that direct view of the window may be possible if not installed properly and that care must be taken in selecting a suitable location. The report continues:

> However, until more data is available showing the advantages of a more complicated, perhaps nonsymmetrical response sensitivity, a symmetric design is the simplest and therefore the best. A symmetrical response simplifies the commission process by making the sensor placement insensitive to orientation.

Spatial Sensitivity

Bierman studied the spatial sensitivity of various photosensors. This study found a significant variation in the spatial response. This study found that the photocells varied from a narrow cone of view (less than 30 degrees) to a wide cone of view (larger than 60 degrees). They found that none of the photosensors had a cosine-corrected cone of view although several approached this view. They also stated that certain spatial sensitivities were appropriate for use with certain control algorithms.[1]

The LRC prototype has a viewing cone of almost 90 degrees. The report states that they determined that adequate performance could be realized from this cone of view without bearing the additional expense of providing a cosine-corrected diffuser.

In theory, widening the cone of view should improve the system response. However, as stated previously, viewing the window is not beneficial. In addition, the wider cone of view could also cause the photocell to directly view the upward component (or indirect component) from a direct/indirect pendant fixture.

Another consideration with the cone of view is that the size of a particular plane that is viewed changes with the mounting height of the photocell. As mentioned above mounting on the lower side of a pendant fixture is an increasingly common alternate location. In many cases, if mounted above a desk this will reduce the "photocell to task" distance from 6'6" to 4'6". If for example the photocell has a sixty degree cone of view, this lowered height will reduce the diameter of the cone of view at the task level from 6' 6" to 4' 6". Corresponding to this change will be an increase in sensitivity to a change in reflectivity of any surface within the cone of view.

In reviewing the available photocells, we observed that some photocells used a diffuser while others used a concentrating lens, typically a Fresnel lens. It is not clear if a concentrating lens offers any advantage over a diffuser. The two photocells that appeared to have diffusers only were the Lutron MW-PS-WH and the Sensor Switch CM-ALC.

<u>Spectral Sensitivity</u>

Most photocells currently use silicon-based photodiodes that are sensitive to a broad energy spectrum ranging from less than 300 to about 1100 nm. The Bierman study found that all of the photosensors had at least minimal filtering to narrow the sensing range of the photodiode and attempted to bring the sensing range closer to the CIE photopic function. However, they found that almost all of the tested photosensors measured energy in a broader range than the photopic curve and were sensitive in both the near UV region and the near IR region. They also found a dramatic increase within the modeled space in the spectral content for wavelengths longer than 680 nm. The Beirman study theorized that these wavelengths were absorbed less by typical room surfaces than the shorter wavelengths. They said proper filtering of the IR is extremely important to the proper operation of photosensorsand estimated that this spectral mismatch produces errors over reporting the contribution of daylight by up to 40 percent.[1]

The LRC prototype uses a photodiode filtered by a glass filter that is constructed of readily available filter materials. Their filter approximates the photopic curve. They approximate that their filtering results in only a five percent error in signal when measuring daylight compared with a typical photosensor that has a 31 percent error in signal.

The one product that is currently being marketed that does not use a photodiode is the Watt Stopper LS-201. This device uses a green LED as a light receptor. The LED senses light only in the lower portion of the visual spectrum. (In one of the project team's tasks under this PIER project, we will be collecting test data on the actual spectral response of this photocell.)

No current photocells available for daylight responsive dimming control attempt to differentiate between electric light and daylight. Lee et al. has suggested that the control response of the daylight responsive dimming could be improved by differentiated the two sources of light. They created a method of distinguishing the two sources of light although their actual method of distinguishing light sources is not fully described in the study. [5]

This type of differentiation of light sources may also help to simplify the commissioning of the device. For example, many current photosensors require adjustment under both a daylit condition and a non-daylit condition. Perhaps with the photocell smart enough to calculate the daylight contribution and the electric light contribution, the device could be commissioned during one visit under daylit conditions. The device could be smart enough to calculate the nighttime setting. (The LRC prototype achieves this single step commissioning of a closed loop proportional device by capturing the sensor signal to workplane illuminance ratios with and without the electric lights on.). Another possible use for differentiating light sources would be to prevent over dimming of the electric lights. To satisfy challenging applications, a control scheme could be created that maintains a minimum electrical light contribution, not by fixing a minimum voltage as is provided by some of the open loop proportional control devices today but, by measuring and maintaining the actual electric light contribution.

Open vs. Closed Loop Strategies

Daylight responsive dimming systems have been categorized into open-loop and closed-loop devices. While these terms do in part imply a different control strategy, they predominately refer to the strategy for collecting information about the daylight contribution to the controlled zone. An open loop sensor only reads the daylight levels while a closed loop sensor reads both the daylight and the electric light. Because the closed loop device reads the level that it controls, its control scheme inherently uses feedback.

We found that the majority of marketed devices are intended to be closed loop devices. We found only two products marketed as open loop devices, the Watt Stopper's LCD and Lutron's Digital Microwatt. Rubinstein found that the best correlation of photocell signal to workplane illuminance was for a closed loop photocell with proportional control.[4]

Control Issues

One of the most prevalent control devices of this type, the ceiling mounted photosensor, is typically powered by the control voltage provided by the ballasts. These devices have been characterized as passive devices because they provide only variable resistance to lower the control voltage signal. This strategy simplifies the wiring of the photosensors because additional wires for powering the photosensor are not needed but this strategy also introduces operational and calibration issues. First, it limits the control signal range. In the example of 0-10 VDC ballasts, it effectively limits the control range from 2-8 VDC because the photosensor typically requires a voltage potential of at least 2 volts to operate. In contrast, devices that are externally powered avoid this issue and are able to provide dimming over the full 0-10 VDC signal. Second, the operating characteristics of these devices, and thus the calibration adjustments, can be dependent on the characteristics of the control circuit to which they are connected. These devices provide control by sinking current to maintain a voltage signal to the ballasts. As the light level varies from the desired level, the photosensor responds by sinking more or less current. The problem is that the amount of current on the circuit is dependent on the number of ballasts connected to the control circuit. Therefore, while the lighting requirements for two photosensors may be similar, their calibration adjustments may be quite different based on the number of connected ballasts. This potential for inconsistent settings may prevent the use of the standard calibration settings to speed calibration.

Typically, more complex devices that are powered separately from the ballast control signal can be set to maintain a level independent of the current flow on the control circuit. They offer the advantage that the adjustments from one zone can be copied to another zone and can therefore be repeated from zone to zone.

Another factor contributing to more or less current on a control zone is the number of ballasts connected to the control zone. Different models of ballasts supply different amounts of current. For example, one manufacturer's model of a dimming ballast using 277 VAC supplies nearly half the current on the control signal than the same manufacturer's ballast for 120 VAC.

Mating of photosensors with ballasts also introduces variations in response that may lead to providing too much or too little light to maintain workplane illuminance. The control response of each photosensor varies due its photocell characteristics and control algorithm. Likewise, the control response dimming ballasts is not standardized. Information provided by the manufacturers indicates variability between manufacturers of dimming ballasts while maintaining conformance to the 0-10 VDC standard. Different models of ballasts from the same manufacturer may also vary in their control response. For example, the voltage signal at which the ballasts begin to dim or complete dimming have not been standardized.

While the actual control error introduced by mating the different control responses of various photosensors with various ballasts has not been characterized, the ability to linearize the combined response is possible with future photosensor designs. The LRC prototype provides an example. The photocell samples the light levels produced by the controlled fixtures at various voltage signals. It then characterizes the light level output at various signal levels.

Types of Control Response

Rubinstein classified daylight responsive dimming devices as using one of three types of control algorithms to convert the measured light level into a control signal.
One of the identified control algorithms is Integral Reset. Rubinstein also used the phrase "constant setpoint" for this control strategy.[4] Several studies have shown that Integral Reset does not work satisfactorily in daylight responsive dimming applications for several reasons:

a. Current technology photocells over report the visual component of daylight resulting in over dimming.

b. In sidelighting applications, the ceiling illuminance is likely to rise at a greater rate in comparison to the workplane illuminance under daylit conditions. Therefore, the photocell senses a greater percentage increase in light level than is representative of the increase in the work plane illuminance.

c. There is an apparent human preference for an increased light level as the daylight increases because at the maintained light levels the space is less bright in comparison to the view out of the window.

Using a sliding setpoint control has been shown to be more effective in maintaining the desired illuminance levels in several studies including Rubinstein[4]. A key provision of sliding setpoint control is that the percentage of control response to the daylight contribution is adjustable. To set this adjustment, sliding setpoint control has typically required commissioning under two distinct conditions. The first condition is "nighttime" or non-daylit conditions. The second is with a daylight contribution that is significant but does not exceed the level at which full dimming should occur. As an alternative, the LRC prototype has devised an innovative scheme to allow commissioning in a single visit. When commissioned the prototype records the workplane illuminance levels and the sensor illuminance levels. From this information, the prototype calculates the "sensor to workplane illuminance" ratios under electric light only conditions and daylight/electric light conditions. These ratios are plugged into the system's sliding setpoint control algorithm.

Little indication is available describing the type of the control algorithm that is being used by a given product. The Specifier Report written by the National Lighting Product Information Program (NLPIP) illustrates how relevant this information is to the application of a product [2] yet this is the only place that a particular product's control strategy was identified. In subsequent work by Bierman and Mistrick the control strategies of seven unnamed devices were identified.[1,3] However, the information was not provided to match the tests with an actual product. In addition, in reviewing the manufacturer's literature, we found almost no indication of the control algorithm utilized except in devices using open loop proportional control. In this case, the information was given primarily to explain the proper photocell placement. The best indication of the control algorithm is provided by the available adjustments and the description of the time of day and conditions when the system can be calibrated. A closed loop proportional algorithm is likely to require a nighttime and daytime adjustment as well as have a nighttime setpoint and some type of daytime adjustment.

Of the eight photosensors in the Bierman[1] study, three were classified as constant setpoint devices and five were classified as sliding setpoint. One of the constant setpoint devices was the LS-30 manufactured by the Watt Stopper. The LS-30 has since been replaced by the LS-201 that provides sliding setpoint control.

Some marketing literature of other manufacturer's products may provide clues that their products utilize constant setpoint control. For example, the Lithonia DEQ LC refers to "PID automatic daylight dimming mode," PID is a control strategy that combines proportional and integral and derivative control to maintain a constant setpoint.

It may also be likely that any building automation system that is providing daylight responsive dimming is utilizing a constant setpoint strategy because this type of control is widely used in building automation systems. In addition, many building automation systems provide pre-programmed constant setpoint control loops as well as documentation on how to use it. It is generally considered the best form of control for temperature control, fan speed control and other analog building control schemes. However, the reasons that constant setpoint control has been found to provide poor control for daylighting responsive dimming are not intuitive and are specific to the daylight responsive application.

Occupant Adjustment or Override

Most of the self-contained photosensors do not provide the occupant with an ability to raise or lower the electric light level. The PLC-Multipoint EDS/AB is an exception with the wall switch overriding the automatic dimming control. Many of the more complex units provide the ability to override the automatic dimming function. This override is maintained until the device is manually switched back into automatic control. The Watt Stopper LCD controller provides a hard override but offers the ability to automatically return to automatic dimming control. Following a hard override, the controller returns to automatic dimming mode when the end of occupancy is indicated.

The LRC prototype has provided the ability for the occupant to make light level adjustments while maintaining automatic dimming. If the occupant wants more or less illumination, then they press a button on the wall switch that adjusts the automatic dimming response. This adjustment is particularly relevant to occupant satisfaction during the transitional periods in the morning and afternoon when they could be sensitive to changes in light levels. However, because these transition periods are of relatively short duration, providing this adjustment should not greatly impact the energy savings.

Limited Coordination of Dimming with On/Off Control

Typically, the self-contained photosensors do not provide any coordination of On/Off Control with dimming. They only provide dimming. More complex systems provide the logic to turn the lights off after the lamps have been fully dimmed for an extended period. For example, the Watt Stopper LCD switches the lights off after the lamps have been dimmed to minimum for a time delay of 12 minutes. Similarly, the LRC prototype switches the lamps off after being fully dimmed for 10 minutes. Also both of these devices allow the same controls to offer the occupant a manual off control. The coordination of On/Off control with dimming could be further developed to provide user enhancements such as a slow restore rate or a slow fade rate or a dim before disconnect.

Commissioning

Proper commissioning of daylight responsive dimming controls is critical. Without proper commissioning, these devices have been shown to perform poorly. Most of the existing devices are not designed to provide some level of control prior to commissioning. In addition, most of the existing devices provide considerable deterrent to proper commissioning. The time and attention required for commissioning of these devices is considerably more than other similar building controls. In some instances, the cost of commissioning a device properly can approach 50 percent or more of the cost of the device.

For most photosensors, the adjustments are on the face of the photocell, or under a front cover, in close proximity to the opening for the photocell. With this configuration, the commissioning agent cannot help but influence the readings of the photocell when making adjustments. Asking the commissioning agent to step away from the photocell is further deterred because they have to stand on a ladder to make the adjustments. Therefore, asking them to step away is actually asking them to climb down from the ladder and also to move the ladder. In many situations having to use a ladder is itself a deterrent to proper setup. It is particularly an annoyance for any adjustment that should take place after occupancy because bringing in a ladder to an occupied space would interfere with the occupant’s productivity.

Even devices where the adjustments have been removed from the photocell location provide deterrents. For example, Lutron’s Digital Microwatt has the daylight adjustment level at the remote controller. However, their instructions require that the adjustment be made during a time when some daylight is present but less than the daylight level at which full dimming occurs. These instructions define a small window of opportunity, in some applications less than half an hour a day. In a large installation, if only one or two devices can be commissioned on a given day, then rigorously commissioning these devices could extend over a long period. This requirement clearly leads to encouraging commissioning shortcuts.

Similarly, many sliding setpoint devices require adjustment under a no daylight or nighttime condition and another adjustment under daylight conditions. Requiring two adjustments adds special coordination for the commissioning agent. It requires scheduling of personnel during off hours as well as gaining access to the facility.

There is also a substantial range in complexity of the setup parameters of the devices. For many photosensors, the adjustment consists of one dial. However, the Watt Stopper LS-201 is an example of a more complex adjustment with four dials and one jumper. Other systems can provide an assortment of adjustments. For instance, the Watt Stopper LCD has adjustment to set the ramp rate, the fade rate, the minimum signal and the maximum signal. While the simplest present adjustments may not provide enough flexibility to meet the application, the more complex adjustments may be a deterrent to proper adjustment because adjustment is not intuitive.

The LRC prototype is the first device that we are aware of which is attempting to do some self-commissioning. It does two types of self-commissioning. First, during the commissioning it records the ratios of sensor signal to work plane illumination under both daylight and electric light conditions. The device self calculates these two values. Of particular importance is that this set of calculations allows this sliding setpoint device to be commissioned during one visit. The second type of commissioning that it does is to measure the light output response of the ballast. While most other products do not compensate for the individual and potentially non-linear response of the ballast, this device does its own compensation.

The challenge of properly commissioning these devices gets magnified on large projects. While the commissioning is generally repetitive, few devices provide any tools to simplify multiple commissioning. For instance, most devices need to be physically adjusted. (The exceptions are some networked systems.) Also, most passive devices require individual adjustment based on the number and type of ballasts connected. The settings for a device with six ballasts connected are not likely to be the same as a device with 12 ballasts connected. In addition, the sensitivity of the adjustments of most devices make it very difficult to set the devices by matching the positions of the dials. Given the variations in the analog electronics and the sensitivity of the devices, the only reasonable adjustment must be done while observing the controlled lamps and ballasts.

One interesting device that may have the potential to simplify commissioning is the Phillips TRIOS Luxsense that is currently being marketed in Europe. This device is adjusted by rotating an aperture to let more or less light hit the photocell. With this device, the adjustments are not adjusting electrical signals. Therefore, this type of design may offer the potential for quick, repetitive commissioning.

Networked devices may also offer the promise of simplifying repetitive commissioning. Zones that have been identified as similar may have the same setup parameters copied from zone to zone. However, it is not clear that any of the networked systems address the complexity of the daylighting requirements.

Lamp Burn-In

Many manufacturers recommend that new fluorescent lamps burn at full output for an initial period before being dimmed. Typically, this period is defined as 100 hours. In their literature, they state that not providing a correct burn-in will shorten lamp life. Anecdotal evidence suggests that premature lamp failures may be occurring due to incorrect burn-in.

The only existing product that we identified to have a burn-in timer was Lutron's Digital Microwatt. On powerup, this device limits automatic dimming for 100 hours before commencing automatic dimming.

Networking Technologies

There are many benefits of having systems networked. As previously mentioned, commissioning can be simplified. There is also the ability to remotely fine tune a system for optimal performance. There is also the ability to centrally report a system failure. It may be possible to do side-by-side comparisons of comparable rooms in ways where it is unlikely for a non-networked system to be compared. Collection of performance data may also be gathered over time and formatted into reports. These histories may be useful in auditing the system performance as well as showing a building owner the benefit that these systems provide.

We believe there are some emerging trends in networking that may influence future daylight responsive dimming systems. DALI (digital addressable lighting interface) is a protocol for communicating with ballasts. It appears to provide many of the advantages found today only in proprietary systems.

DALI defines a set of lighting specific commands. It defines a standard for 100 steps of dimming with each dimming step equal to a perceived 1 percent change. To provide this perceived change, the actual signal change at higher light outputs is many times greater than the actual signal change at lower light outputs. Also within the DALI standard is a definition of the light level at each dimming step. Thus DALI ballasts should eliminate the individuality of the response of 0-10 VDC dimming ballasts available today. The only DALI daylight dimming product that we were able to identify was the Helvar DigiDim.

LBNL is developing a lighting equipment communication network based on embedded device networks. In this model, lighting equipment (ballasts, sensors and switches) would be enhanced with embedded devices that can communicate over a low-cost wired network. The Integrated Building Environmental Communications System or IBECS is an implementation of embedded device network applied to lighting controls. The protocol underlying IBECS, the 1-Wire protocol, is part on an Institute of Electrical and Electronics Engineers, Inc. or IEEE Standard P1451 that is an approved standard for sensors and actuators. Although the IEEE Standard was not developed by the lighting industry it is applicable for many lighting control components including ballasts, sensors and switches. Since the standard provides “plug-and-play” technology, it may be appropriate to overcome some of the barriers facing advanced lighting control systems.

Other networking standards that are impacting daylighting controls include Ethernet and LonWorks®. There are presently photocells that will share information over a LonWorks network. It is anticipated that each of these networks will serve to integrate information from smaller local networks into a building-wide network.

While networking standards may ultimately change daylighting controls, any exploration of the networking technologies is likely to be beyond the scope of this project. When any of these networking technologies emerges as cost effective for building control, then daylight responsive dimming controls are likely to offer the advantages of being networked.

Application Issues

There are also a number of application issues that either do not have present solutions or applications for which the specific requirements are not fully understood.

Pendant Fixtures

The use of pendant fixtures is now established as providing very high quality lighting. Typically, these lights shine a percentage of their light upward as well as downward. The upward light is reflected in a diffuse manner onto the work plane. This type of fixture is often referred to as a "direct/indirect" fixture.

For a daylight responsive dimming system, this type of lighting presents challenges. First, the upward component of the light may strike a ceiling-mounted photocell directly thus breaking the expected relationship that the sensor receives reflected light from the work plane, walls, and floor. If mounted above the direct/indirect fixture, the illuminance hitting the photocell may overpower the photocell. The application instructions for photocells, when they address this application, recommend that the photocell be mounted in a darker portion of the ceiling away from the pendant fixtures. In many cases, there is no such dark spot or it is a location that is not representative of the zone undergoing the daylight responsive control.

One common solution today is to have the photocell mounted onto the face of the pendant fixture or mounted onto an endcap of the fixture. This location adds additional issues and may ultimately not be the best location. First, it moves the photocell closer to the work plane, thus reducing its cone of view. By reducing the cone of view, it makes the photocell more responsive to changes in reflectivity. Second, the photocells must be factory installed into the fixtures. Once installed there are no options to move them. Mounting on the fixture thus takes away any flexibility at installation to move the photocell to an optimum location. It also requires a multi-disciplinary coordination that is not typical in the industry today. Third, it may also promote zones that match up with the fixture installation but do not necessarily make the best control zones.

Ultimately, mounting on the ceiling may be a better location for most applications. However, mounting on the ceiling will require some method of "seeing thru" the light striking the photocell directly. A strategy to see thru this light may be based on the understanding that this component is both measurable and consistent. Therefore, a smart sensor could measure this component and then effectively ignore it.

Coordination with Motorized Blinds and Louvers

Another application issue that is generally not addressed in this country is the coordination of motorized blinds and louvers with daylight dimming responsive controls. Blinds are typically used for reducing daylight coming from windows and louvers are typically used for reducing daylight entering from skylights. It is rare for a building in this country, even in daylit-aware designs, to have automatically controlled blinds. While motorized louvers in skylight lightwells are more commonly installed, typically the louver position is manually adjusted to darken the room or to reduce glare. When the louvers are automatically positioned to maintain light levels, they are still rarely integrated with the lighting control system, except perhaps in museum spaces.

In Europe, motorized blinds providing automatic glare and daylighting control are much more common. One common method of integrating the control of the lights and the blinds is to share light level information via a LonWorks building control network. While it is not clear that any fully integrated blind and lighting system exist, this type of integration is a step forward.

Several studies have shown the impact of blind positioning upon the daylight levels in the room as well as the impact of blinds on the ceiling to work plane illuminance ratios. Any adjustment of the blind angle is likely to change the relationship. Mistrick also found that any photosensor commissioned without the blinds being active is likely to result in the space being underlit when the blinds are employed.[3]

Multizone Control

Multizone control consists of controlling two or more zones at different dimming rates based on the signal from one photocell. Many spaces will have two or more zones of control. For example, in a sidelighting application the row of fixtures closest to the window is likely to be one zone. The next row of fixtures moving away from the window is likely to be another zone. There are several reasons for providing multi-zone control from one device. Where both rows are dimming, using one control device prevents the potential interaction of two zones being controlled independently. When controlled by two independent devices, one of the zones may dim down thereby reducing the illumination seen by the photosensor in the adjoining zone. In response, the photosensor in the adjoining zone may start a potentially annoying cycle of interaction by starting to ramp up.

However, it is not clear that one photocell in a closed loop system could adequately represent two zones. No such device currently exists. The challenge would be to easily calculate the relationship between the two zones. Possible solutions might include having multiple sensors that could communicate. Through the passing of the illuminance levels in each zone and possibly the components of the illuminance, the two photosensors could prevent the control instability caused by the interaction between zones.

Sidelighting versus Toplighting

Another application area that is largely unstudied is the difference in control requirements between daylight applications that are sidelit versus toplit. We believe there is no apparent product differentiation for these two applications. All existing dimming products appear to be directed toward sidelighting applications while also working with toplighting applications. This is in contrast to the products for On/Off switching, which do have products designed specifically for toplighting applications. As an example, some photocells for toplighting applications are sold in two or more sensing ranges. Whether further study leads to a need for greater product differentiation is unclear. However, it is expected that further study will lead to more specific application information for each application. Mistrack has suggested that open loop control is likely to be more successful in a toplighting application while closed-loop control is more effective for a sidelighting application.[3]

Future Development

The recommended summary for this report is to identify the priorities for improving the state-of-the-art photocell technology. The design and research objectives for our upcoming work under the PIER LRP Project 3.3 are listed below.

- We will focus our efforts on building a closed loop control device while attempting to overcome the limitations found in presently available closed loop devices.

- We will create a device, which is microprocessor based, and bring improvements possible because of the technology. As an example, the photocell sensing range shall be autoranging so that the resolution of the sensing range is appropriate for the light level. Much greater resolution will be provided at lower levels than at higher light levels because occupant perception of light level changes at lower levels is likely to be greater. The device shall be externally powered and therefore avoid the issues introduced by passive devices.

- The photocell for this device is to be ceiling mounted with:

    1. A method of blocking the photocell's view of the window.
    2. Filtering to achieve a spectral sensitivity that approaches the photopic curve.
    3. A wide spatial sensitivity to reduce the impact of a local change in reflectance within the cone of view.

- We will attempt to provide solutions or control enhancements for mounting on the ceiling above direct/indirect pendant fixtures. These control enhancements may include having the photosensor differentiate light sources.

- The control algorithm shall use sliding setpoint control while overcoming the typical commissioning necessity of being adjusting under a no daylight and a daylight condition. The commissioning process shall attempt to capture the sensor to typical work plane illuminance ratios for both electric light only and daylighting conditions to use in the control algorithm.

- We will explore means of simplifying the commissioning requirements with particular emphasis on providing tools for repetitive commissioning. Commissioning during one visit is a priority. Repetitive commissioning should be accomplished by a simplified method of copying setup parameters from a commissioned device to subsequent devices without the necessity for testing the individual response of each successive device.

- We believe that any design shall remove the adjustments from the photocell location. Adjustments must be able to be made without blocking the view of the photocell. It is also an objective that the adjustments be made from the ground so that no ladders are required. It is also important that adjustments be made without disrupting the occupants of the room.

- We will attempt to identify ways in which to make the device smart out of the box with the default settings for adjustments being set to provide some amount of control prior to commissioning.

- We will research the need for providing an automatic burn-in timer.

- We will coordinate On/Off control with dimming to provide shut off following full dimming as well as provide dimming before disconnect, slow restore, and slow fade. We will also look for opportunities to optimize the coordination with occupancy control.

- We will provide the occupant with a manual adjustment of the desired light levels provided by the automatic dimming control while greatly limiting the occupant's use of hard overrides.

- We will create a stand-alone system while anticipating future networking capabilities.

- We will look at and attempt to address the requirements for control of multiple adjoining zones both in reducing the interaction between zones and in simplifying the commissioning process.

- We will attempt to differentiate the control requirements of applications that are predominantly toplit with applications that are primarily sidelit and work to develop a product that can function under a variety of daylight configurations.

Daylight Responsive Dimming Product Information

Manufacturer	Model Number	Type of Device	Currently Marketed in U.S	Web address
Cutler-Hammer	POW-R-Command 100	Panel based dimming	Yes	http://www.cutler-hammer.eaton.com/
Danlers	CEFL	Photosensor	No	http://www.danlers.co.uk/
Douglas Lighting Controls	WPC-5700	Passive photosensor	Yes	http://www.douglaslightingcontrols.com
Easylite	Daylite Harvester	Photocell	Yes	http://www.easylite.org/
Ledalite	Ergolight	Integrated fixture control	Yes	http://www.ledalite.com/
Helvar	Digidim	DALI-based room control	No	http://www.helvar.co.uk/ukdigidim.htm
Honeywell	EL 7365	Photocell	Yes	http://www.honeywell.com/
Honeywell	EL 7305	Dimming Controller	Yes	http://www.honeywell.com/
Precision Lighting	JustRightLight	Ballast with Integrated Control	Yes	http://www.justrightlight.com/
Leviton	ODCOP	Photocell	Yes	http://www.leviton.com/
Leviton	DPC	Room Controller	Yes	http://www.leviton.com/
Lighting Control and Design	PCI	Photocell	Yes	http://www.lightingcontrols.com/
Lightolier	Photoset	Photosensor	No	http://www.lolcontrols.com/
Lightolier	DaylyteMode Controller	Room controller/ scene controller	Yes	http://www.lolcontrols.com/
Lithonia	LEQ LC	Room controller	Yes	http://www.lithonia.com/
Lithonia	LEQ DPC	Photosensor	Yes	http://www.lithonia.com/
Lutron	Digital Microwatt	Room controller	Yes	http://www.lutron.com/
Lutron	MW-PS-WH	Photocell	Yes	http://www.lutron.com/
Luxmate	DSI-TLC	Dimming Controller	No	http://www.luxmate.com/
Novitas	01-PDI	Photocell	Yes	http://www.novitas.com/
PLC-Multipoint	EDS/AB	Photosensor	Yes	http://www.plcmultipoint.com/
Philips	TRIOS Luxsense	Photosensor	No	http://www.philips.com/
Philips	Lumisense	DALI based photocell	No	http://www.philips.com/
Sensor Switch	CM-ALC	Photosensor	Yes	http://www.sensorswitch.com/
Triatek	Lumiys	Panel based dimming	Yes	http://www.triatek.com/
Unenco	DTD	Photosensor	Yes	http://www.unenco.com/
Watt Stopper	LCD-101/ LCD-103	Dimming Controller	Yes	http://www.wattstopper.com/
Watt Stopper	LS-201	Photosensor	Yes	http://www.wattstopper.com/

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